

GENERAL AND TECHNICAL CONSIDERATIONS FOR IMPLEMENTING HIGH SPEED RAIL SYSTEMS IN AUSTRALIA

Hadi Khabbaz¹ and Behzad Fatahi²

¹Associate Professor, ²Senior Lecturer, Centre for Built Infrastructure Research, School of Civil and Environmental Engineering, University of Technology Sydney (UTS), Sydney, Australia.

ABSTRACT

Australia has a number of medium speed rail services such as the Prospector, which runs from East Perth to Kalgoorlie, at speeds of up to 160 km/hr. Speeds as high as 210 km/hr have been reached by the tilt train from Brisbane to Rockhampton. Although there are a few medium speed rail systems in Australia, there is not a passenger rail transport with the high transit speeds seen in other countries. This paper presents the feasibility of implementing high speed rail systems in Australia by looking at the main elements that a high speed train is composed of. This paper also reviews the performance of high speed rail systems around the world and the factors contributed to their success made them successful. The main objective of this study is to look at how the solutions from overseas and how the technical requirements particularly the geotechnical aspects of tracks for a high speed rail system can be applied in Australian existing and new tracks. Australia has its own unique demographic, geographic and economic characteristics and the aim is to identify where there are overlaps between Australia's characteristics and countries with high speed rail systems. High speed rail transport might not necessarily be one the best solutions for the transportation at present in Australia, but it can be what a nation needs to succeed in its future transportation system.

1 INTRODUCTION

Growing congestion in major cities, increasing population and getting higher commuting across cities, have resulted in massive investment in transport network in Australia. The annual cost of traffic congestion in Australia is estimated at \$10billion apart from an annual road toll of about 1500 and 30,000 injuries (Perry, 2010). Road transport is Australia's third largest source of greenhouse gas emissions. Hence, "business as usual" is no longer an option. Railway and airway systems are other options for faster and safer travels. Obviously air travel offers higher speed than railway. However more time is required for air travels due to boarding (aircrafts have fewer doors than trains), transporting to or from airports, security check, luggage drop and ticket check. In addition, railway stations are usually located nearer urban centres than airports. Rail travel has less weather dependency than air travel and generally they are more comfortable, as passengers can move around the train during the journey.

Railways form an important part of the transportation infrastructure of a country and plays an important role in sustaining a healthy economy. Australian railway organisation should set down clear strategic directions to direct government and industry to ensure that Australia's rail networks are capable of meeting future transport demands. Anthony Albanese the Minister for Infrastructure, Transport Regional Development and Local Government in 2010 expressed that "we are committed to supporting our major cities and tackling the increasing productivity costs of urban and traffic congestion. High speed rail has the potential to cut travel times for people commuting between capital cities like Sydney and growing regional cities like Newcastle and Gosford. Nearly 10 million people live along the east coast between Brisbane and Melbourne, which requires ongoing investment in modern transport infrastructure." (Australian Government - Department of Infrastructure and Transport, 2012). The government has recently organised a committee to conduct a comprehensive feasibility study on developing high speed rail systems by identifying potential rail corridors, undertaking geotechnical and engineering investigations and carrying out the financial and economic modelling to determine the project's viability.

This paper firstly summarises lessons that can be learned from other countries experienced high speed rail (HSR) for a couple of decades. Then, the general considerations and challenges associated with implementing HSR systems in Australia are explained. The main challenges include selection and design of proper tracks, geographical issues, environmental concerns, economics and project costs and construction procedures. The second part of this paper is related to technical issues of HSR systems. The concept of critical velocity for ballasted tracks is described. Various approaches are discussed to improve the ballast layer properties and to enhance the track formation bearing strength, stiffness, resiliency and dynamic properties. Employing concrete slab (ballast-less) tracks is also taken into consideration for HSR systems and their performance is compared with ballasted tracks.

2 WORLD EXPERIENCE OF HIGH SPEED RAIL

High speed rail is a form of mass rail transport that runs at significantly higher speeds than normal rail systems. The approximate maximum commercial speed is 300 km/h for the majority of national high speed railways (France, Spain, Japan, China, Taiwan, Germany, Italy and UK). However, the specific definitions by the European Union include 200 km/h for upgraded tracks and 250 km/h or faster for new tracks (Givoni, 2006). High speed trains travel at their maximum speed on specific tracks or on conventional tracks with standard gauges with avoiding at grade crossing, short radius curves and high gradient (i.e. greater than 2%).

According to Woodward (2012), a Boeing aircraft typically has a cruising speed of 790 km/h and is currently one of the fastest means of travel. In 2007 a modified French TGV train set a land speed record of 574 km/h on ballasted track, which is just slightly short of the Japanese Maglev record of 581 km/h. History has shown that operational speeds tend to eventually follow maximum speeds as technology develops. The concept of very high speed operational trains would therefore appear to be a real future possibility.

2.1 ASIA

Japan was one of the first nations to implement a high speed rail system. Several other Asian countries such as China, South Korea and Taiwan planned and constructed HSR networks.

2.1.1 Japan

In the densely-populated country of Japan, especially the area with 45 million people between Tokyo and Osaka, congestion on roads and rails became a serious problem in the 1950s. The construction of new rail service, named *Shinkansen* (bullet train) began in 1959 and was completed in October 1964, in time for the summer Olympics in Tokyo (Okada, 2007). The 1960s were a time of great economic growth and prosperity. The first *Shinkansen* trains run the 515 km distance with a top speed of 210 km/h and an average speed of 162.8 km/h with stops at Nagoya and Kyoto.

2.1.2 China

In China, plans for the largest high-speed railway network in the world were driven by a combination of capacity constraints on existing lines and a desire to shorten journey times, while promoting development along the route. According to Okada (2007), the construction schedule was significantly accelerated due to additional funding in the stimulus package of 2008 and a number of lines have been due to be completed by 2013. China has recently increased the speed of the existing train lines. Passenger lines now run at speeds over 120 km/h on approximately 22,000 km of track, at speeds greater than 160 km/h on about 14,000 km of track and at speeds greater than 200 km/h even 250 km/h for around 6,000 km of track.

2.2 EUROPE

In Europe, high-speed rail begins during the International Transport Fair in Munich in June 1965, when German Federal Railways operated fast trains with 200 km/h between Munich and Augsburg. The same year, in France, the engineer Jean Bertin invented the *Aérotrain*, a hovercraft monorail train, and built the first prototype (Gourvish, 2010). The European high speed rail network was initially a series of national lines. In other words, there was no 'European Network'. The proposal for an interconnected network came through the Community of European Railways in 1990 and this became the Trans-European network for high-speed rail. The proposed network initiated for three reasons: (1) overcome bottlenecks, as there was a problem with limited capacity on critical sections of the network, (2) increase speeds, as in some parts of the network, the speeds were too low and (3) improve accessibility to provide access to some remote regions.

2.2.1 France

The National Corporation of French Railways launched the *Train à Grande Vitesse* (TGV) program to create a French high speed rail system. Its debut line was launched in 1981 linking Paris and Lyon. Initially the line trains ran at normal speeds but in 1983 the line was fully operational and the journey over 409 km lasted approximately 2 hours.

2.2.2 Germany

In terms of network size, Germany's high speed train, the ICE (Inter-City Express) currently ranks fifth in the world, with about 1,300 km of lines in operation, behind China, Japan, France and Spain. Germany plans, over the next few years, to construct an additional 1,000 km of lines (Givoni, 2006). With over 10 operating lines, the HSR connects many of the country's populated centres and these rails in Germany have an 8.4% share of the passenger transportation market overall. However, most German HSR lines operate at top speeds of 250-280 km/h, somewhat slower than other

European countries. As an example, a trip from Berlin to Hamburg, for a distance of 255 km, takes 1 hour and 50 minutes.

2.2.3 United Kingdom

Britain's high speed rail technologies began in the 1970s. They, rather than building new tracks, decided to develop rolling stock, which would achieve high speeds on existing tracks. The advanced passenger train (APT) was developed, but was phased out due to technical problems. Those diesel powered trains achieved speeds of up to 238 km/h (Gourvish, 2010). In 2009, *High Speed Two Ltd* was established; its aim was to develop proposals for a high speed railway link between London and the West Midlands. At present the route serves some of England's most populated cities, including Leeds, Manchester, Birmingham and London.

2.3 MAIN MODELS OF HIGH SPEED TRAINS

As explained in Section 2.2, many countries have adopted the high speed rail as a transport solution. The length of high speed rail around the world has been increased almost exponentially within the last 50 years, as shown in Figure 1. It is increasingly been seen as a more viable transportation solution.

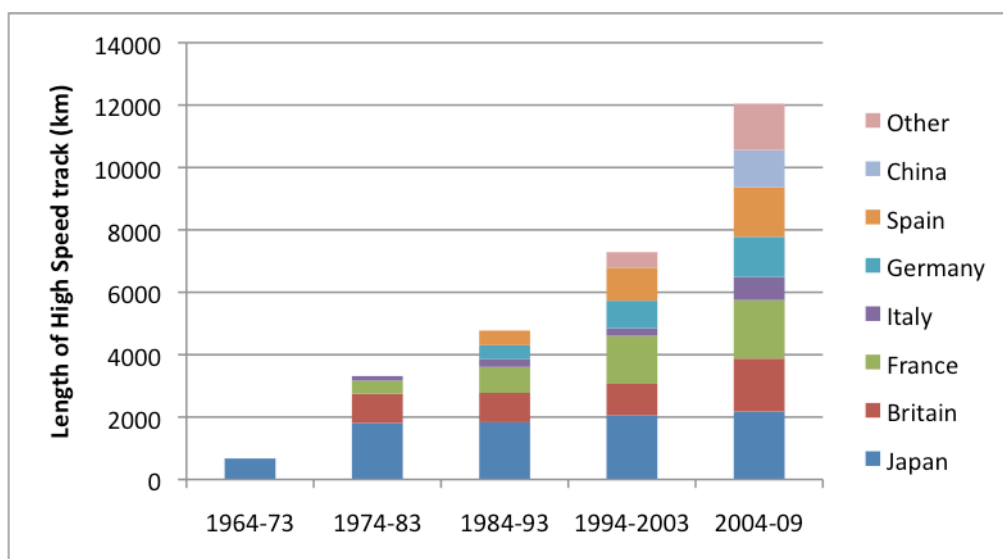


Figure 1: Total length of high speed rail track in the world. The graph created based on data taken from Gourvish, 2010)

The different needs and special characteristics of different countries pursuing the development of HSR operation have led to the evolution of various models of HSRs. The Japanese *Shinkansen*, which was the first modern HSR in operation, can be considered as the base model. Subsequently, three other models have evolved according to Givoni (2006).

2.3.1 Shinkansen

It is a complete separation from other rail services. A unique feature of the *Shinkansen* was the new dedicated line, which in the case of Japan was required, since the conventional railway network had a narrow gauge and could not support the HSR. This isolated the *Shinkansen* services from the rest of the railway system in Japan. The geographic features of Japan together with the requirement to avoid tight curves and steep gradients (to allow for high speeds) resulted in many tunnels and bridges along the route. A total of 30% of the Japanese *Shinkansen* lines run through tunnels (Okada, 2007) leading to very high construction costs. Structure breakdown of the *Shinkansen* lines are approximately: 20% track bed, 10% bridge 30% viaduct and 50% tunnels.

2.3.2 TGV

The French TGV, which began operation in 1981, resembles the *Shinkansen* in purpose, but differs in design philosophy. The most significant difference between the TGV and the *Shinkansen* is probably the ability of the former to operate on conventional tracks as well, which allows the TGV to use the conventional lines as it enters and leaves the city centres, leading to significant cost savings. It also means that the HSR can serve regions with no HSR infrastructure and specifically serve parts of the network where at present the demand is not high enough to justify the construction of dedicated lines. Germany's high speed train, the ICE (Inter-City Express), follows the TGV model, mainly in the compatibility feature. It deviates from the TGV and the *Shinkansen* models by adopting a mixed-use line, meaning the

line is used for both passenger and freight transport. This feature turned out to be a disadvantage since it led to high construction costs (to support the higher load of freight trains) and low utilisation of the lines, since freight trains operate at much lower speeds.

2.3.3 The Tilting System

On many routes demand is not high enough to justify the cost of constructing new tracks that allow high-speed operation. This problem was solved by the tilting train model, but at the price of lower speeds. To allow higher speeds on conventional lines with tight curves, the train tilts as it passes through curves. By simply tilting the train in tight radius curves, the discomfort that passengers may feel from the centrifugal force, as the train goes at high speed through curves, is solved. The bogies remain firmly attached to the rails, while the body of the carriage tilts, and hence compensates for centrifugal force (Figure 2). This principle is adopted by many countries as a cheaper alternative to the TGV and *Shinkansen* models. The Swedish X-2000 and the Italian (ETR-450) are running on conventional rail using the tilting mechanism, thus avoiding the price of expensive new tracks, but reaching a maximum speed of 210 km/h (X-200) or 250 km/h (ETR-450). Today, a tilting mechanism is also used on TGV trains and all the new *Shinkansen* models.

2.3.4 Maglev System

Magnetic levitation (MAGLEV) technology was first tested in the 1970s, but it has never been in commercial operation on long-distance routes. The technology relies on electromagnetic forces to cause the vehicle to hover above the track and move forward. In practice, the aim is for an operation speed of 500 km/h. In 2003, a MAGLEV test train achieved a world record speed of 581 km/h. The special infrastructure required for MAGLEV trains means high construction costs and no compatibility with the railway network. The MAGLEV is mostly associated with countries like Japan (Figure 3) and Germany, where MAGLEV test lines are in operation. In China, a short MAGLEV line was opened in December 2003 connecting Shanghai Airport and the Pudong a financial district in Shanghai, with trains running at maximum speed of 430 km/h.



Figure 2: A Japanese tilting train
Source: http://en.wikipedia.org/wiki/Tilting_train



Figure 3: A Japanies Maglev train
Source: <http://science.howstuffworks.com/transport/engines-equipment/maglev-train.htm>

3 IMPLEMENTATION OF A HIGH SPEED RAIL SYSTEM IN AUSTRALIA

Australia is far behind Europe, Japan, China and many emerging economies by failing to build a high speed rail network connecting the mainland capitals. According to Wright (2009), a fast train network can stimulate Australian domestic construction sector, provide many jobs, whilst being a major step forward to avoid the looming oil and climate crises. High speed rail projects in Australia have been under investigation since early 1980s. The fastest trains in Australia have a maximum speed of 160 km/h, significantly below the internationally accepted speed for HSR of 200 to 300 km/h. On the other hand, many experts believe that the long distances and difficult terrain between major population centres, low population density of inter-urban regions, and present affordability of air travel have made it difficult for HSR proposals to demonstrate financial viability (Arup-TMG, 2001). However, HSR competitiveness is expected to increase with future population increases, particularly that in regional areas.

3.1 PREVIOUS STUDIES

To date a number of comprehensive studies have been conducted for the implementation of a high speed rail system in Australia:

- CSIRO 1984 – CSIRO chairman, Dr Paul Wild spearheaded a study for a high speed rail link between Sydney and Melbourne via Canberra, Cooma, Orbost and Latrobe Valley. Its basis was the TGV technology of the

time. The conclusion was that the project was deemed to be uneconomic after the cost estimation was found to be enormous by almost AUS\$1.5 billion (Williams, 1998).

- The Very Fast Train (VFT) Joint Venture 1986- A group comprised of TNT, Elders IXL and Kumagai Gumi proposed a high speed line from Sydney to Melbourne via Canberra. Numerous feasibility studies were done and there was interest from then Prime Minister Bob Hawke. Eventually the proposal was scrapped after a rejection of a taxation to fund the project in 1991 (Williams, 1998).
- Speed Rail proposal 1993 – Speed rail Pty Ltd proposed a similar route to the VFT corridor limiting it to Sydney to Canberra. It proposed a AUS\$2.4 billion line without changing tax laws. Changes were made from standard high speed rail technology to the cheaper tilt trains. After much debate about cost and expenditure, tenders were requested and four international joint ventures submitted proposals. In December 2000, it was decided that the Speed Rail proposal would not proceed due to funding issues (Canberra Business Council, 2008).
- HSR Study 2011 – This study short listed a number of corridors along the east coast of Australia. It looked at linking Brisbane to Melbourne via Sydney, Canberra as well as numerous regional areas. The report recommends land acquisitions along the corridor before costs escalate. Phase 2, which is yet to be released, will look at the financial feasibility of the high speed rail system and identify an optimum route (AECOM, 2011)

A strategic study on implementation of a high speed rail network on the east coast of Australia was announced by the Minister for Infrastructure and Transport on 5 August 2010. The details are given in the next section.

3.2 HIGH SPEED RAIL STUDY ROUTES

A very comprehensive study called Phase 1 assessment, conducted by AECOM in 2011, defined a recommended study area for further detailed study. Other companies involved in preparation of the study were Grimshaw, KPMG and SKM. The recommended line passes through the east coast of Australia along a coastal route between Sydney and Brisbane, via Newcastle, and an inland route between Sydney, Canberra and Melbourne, as shown in Figure 4. The report has declared that the short-listed corridors have generally lower capital costs for infrastructure and property acquisition than other options. The short-listed corridors broadly follow the alignment of the existing long-distance rail network. This could provide opportunities to rationalise or replace regional rail services with high speed rail services on inter-city and regional routes. The short-listed corridors (Figure 5) minimise potential impacts on national parks and other sensitive lands. The risk-adjusted cost estimate for the implementation of an overall high speed rail network would fall within the range of \$61 billion to \$108 billion (\$2011) depending on the combination of corridors selected.

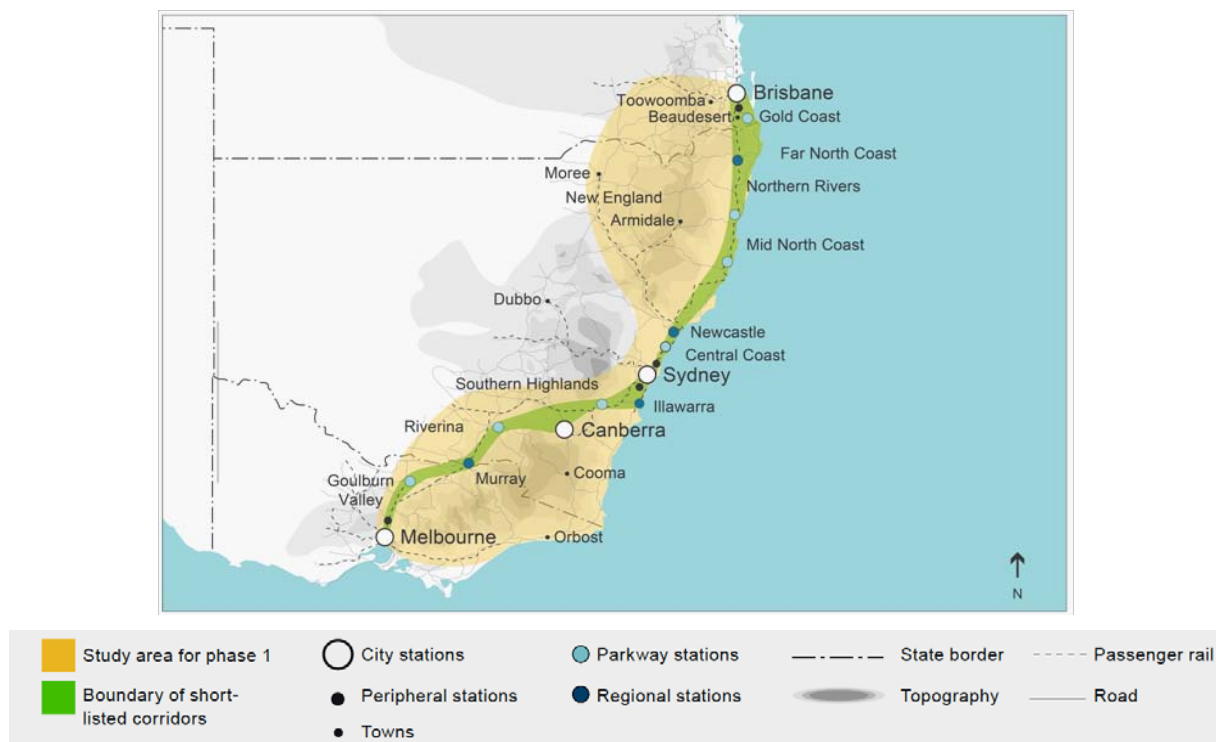


Figure 4: The recommended study area for Phase 2 investigation (AECOM, 2011)



Figure 5: Least costly and most costly corridor combinations (AECOM, 2011)

On the basis of proposed fares, frequency of services and travel times, patronage demand forecasts suggest the preferred corridors could carry approximately 54 million passengers per annum in 2036. Eight million people are projected to travel between Sydney and Melbourne and 3.5 million between Brisbane and Sydney. These forecasts assume inter-city HSR fares comparable with inter-city air fares (AECOM, 2011).

Table 1: Proposed high speed rail study routes (data taken from the Australian Government - Department of Infrastructure and Transport, 2012 and AECOM, 2011)

High Speed Rail Routes	Distance (km)	Travel Time (minutes)	Estimated Costs
Melbourne to Canberra	520-570	110-120	via Albury \$19.5b and \$25.6b
Canberra – Sydney	270-290	70-90	via the Southern Highlands \$10.9b and \$19.2b via Wollongong \$15.0b and \$24.5b
Sydney - Newcastle	115-125	38-42	\$10.7b and \$17.9b
Newcastle - Brisbane	675-765	150-160	via Beaudesert \$20.0b and \$27.8b via Gold Coast \$22.2b and \$40.6b

The key findings of this report, based on the preliminary work undertaken as a part of the study's first stage are:

- Cost between \$61 billion and \$108 billion (in \$2011) to build and involve laying more than 1,600 km of new standard-gauge, double-track (\$38 to \$67.5 million/km)

- Achieve speeds of up to 350 km/h and offer journey times as low as 3 hours from Sydney to Brisbane, and just 40 minutes from Sydney to Newcastle.
- Carry around 54 million passengers a year by 2036 including, for example, about half those who would have flown between Sydney and Melbourne, currently the world's fifth busiest air corridor.
- Offer competitive ticket prices, with one way fares from Brisbane to Sydney costing \$75-\$177; Sydney to Melbourne \$99-\$197 and \$16.50 for daily commuters between Newcastle and Sydney.
- Cut carbon pollution, with emissions per passenger a third of what a car emits. It is assumed that each full train with 450 passengers would be equivalent to taking 128 cars off the road.

3.3 CHALLENGES ASSOCIATED WITH HIGH SPEED RAIL IN AUSTRALIA

Australia has a number of challenges opposing its implementation of a high speed rail system. The geographic conditions of Australia made the construction of a HSR line difficult and costly for two main reasons, the mountainous terrain and the vast distances that would need to be covered. Compared to other nations which have implemented a high speed rail system, the population and the population densities of Australia and its cities are relatively small. However the passengers who use public transportations of some Australian cities are high by international comparisons. The main difficulty that Australia faces, similar to most other nations, is the cost of the lines. The failures to implement the proposals recommended in previous studies have mainly been due to the lack of financial feasibility. Although Australia is well placed economically at this point in time, the length of the line would result in a very high construction cost. The number of commuters would take some time to build up and the required rate of return on the asset may not be achieved for number of years.

3.3.1 Topographical Issues

Australia has no large mountain ranges, such as in Japan or Europe. However, HSRs require very long radius curves and low gradients (generally no greater than 1.5%). Key challenges include the western approach to Canberra through the Brindabella Ranges, the northern exit from Sydney through Kuring-gai Chase National Park and across Broken Bay, the Great Dividing Range near Armidale, and the Border Ranges on approach to Brisbane (Arup and TMG, 2001). Viaducts and tunnels will be required for these areas passing through undulating countryside.

3.3.2 Environmental Impacts

The high speed rail system has also been advocated by many organisations as it will cut greenhouse gas emissions, primarily by reducing air travel. In Australia, air travel accounts for the highest greenhouse gas emission per passenger (240 g CO₂/km) followed by automobiles at 225 g and buses at 75 g. If powered by existing coal power infrastructure, HSR is predicted to emit 150 g per passenger/km, but this could be reduced to 40 g by powering the system with either renewable energy (Canberra Business Council, 2008). The impact of the railway on sensitive environmental areas such as national parks and wetlands has also been an issue. It is clear that any HSR line along the east coast of Australia will necessarily have to pass through national parks and other areas of high environmental and cultural values.

3.3.3 Costs of the Project

As stated earlier, according to the Australian Government's 2011 High Speed Rail Study: Phase 1, the Melbourne-Brisbane line via Canberra and Sydney would cost between \$61 billion and \$108 billion (\$2011), depending on the route selected and whether low or high cost estimates were used (AECON, 2011). It is unlikely that this proposed Australian HSR system to be viable on a privately funded basis alone. The most likely funding arrangement is therefore either the government as the developer or a public-private partnership.

4 TECHNICAL ISSUES WITH HIGH SPEED RAIL SYSTEMS

4.1 CRITICAL VELOCITY

There are many geotechnical issues surrounding the performance of high-speed trains on ballasted railway tracks. According to Woodward (2012), these issues include critical velocity effects, track vibration and settlement and the performance of critical areas and assets such as switches, crossings and transitions.

Researchers (e.g. Madshus *et al.*, 2004; Galvin *et al.*, 2010) expressed that if train speed increases to a certain level, large deformations can occur on ballasted tracks and the structures around rail tracks will commence to experience vibration. The magnitude of this speed, which is commonly called the *critical speed*, is not constant. This speed depends on the ballast and the formation engineering properties. According to Woodward *et al.* (2011), the ratio of train speed to the ground's natural velocity (i.e. Rayleigh wave velocity) is used to evaluate the dynamic interaction between the train and the track. The Rayleigh wave velocity (V_R) can be determined using the following equation,

$$V_R = \frac{0.87+1.12\nu}{1+\nu} V_S$$

$$V_R = \frac{0.87+1.12\nu}{1+\nu} V_s \quad (1)$$

where, ν is the Poisson's ratio and V_s denotes the shear wave velocity, which can be found based on Equation (2).

$$V_s = \sqrt{\frac{G}{\rho}} = \sqrt{\frac{E}{2\rho(1+\nu)}} \quad (2)$$

In this equation, E is Young's modulus, G is the shear modulus and ρ is the density of the soil medium. Table 2 summarises different conditions that may occur on tracks for different train speeds (V_T) and critical velocities (V_R). The track will experience large deflection and associated ground vibration, if the train speed is greater than the critical velocity (i.e. the super critical condition).

Table 2: Dynamic conditions of rail tracks (modified after Yang *et al.*, 2003)

Ratio	Condition
$V_T/V_R < 0.5$	Sub-critical condition
$0.5 \leq V_T/V_R < 1$	Transitional condition
$V_T/V_R \approx 1$	Critical condition
$V_T/V_R > 1$	Super critical condition

New engineering studies are commenced for very high-speed commercial services, particularly in the area of critical velocity or hunting. Hunting is the phenomenon of dynamic oscillation of the bogies, occurring at high speed and leads to dynamic instability and possible derailment. One solution to this problem is the use of yaw dampers and this may increase the safe running speed up to 300 km/h. Yaw dampers are used in locomotives and rolling stock in order to control the rotational movements of the bogie around its vertical axis.

4.2 VARIOUS APPROACHES FOR BALLASTED TRACK STABILISATION

Ballast breaks down and deteriorates progressively under the high train speed, settles differentially due to weak subgrade and poor drainage, fouls due to clay pumping and ballast breakage, and rail tracks buckle due to lack of confining pressure. Ballasted track formation plays a vital role in providing sound track geometry and stability. Many existing tracks in coastal areas in Australia can cause drastic track settlements, as their formation strength will not be sufficient to carry the cyclic loads imposed by the fast trains. If formation is built up of soft or marginal soils, it can become unstable either in a progressive manner or all of a sudden occasion. Progressive shear failure is more likely to occur, which leads to rapid track geometry degradation when exposed to high speed and axle loads by rolling stock traffic. To overcome or reduce the critical velocity issues on ballasted tracks, different mitigation strategies can be adopted. A number of common effective approaches include (1) avoidance poor ground during the planning stages, (2) track reinforcement using geosynthetics, (3) chemical and physical stabilisation of formation to increase bearing capacity, stiffness, resiliency and dynamic properties of the formation, (4) employing prefabricated vertical drains (PVDs) in low-lying areas with high volumes of plastic clays, (5) using native vegetation in semi-arid climates and coastal regions of Australia, (6) selection of high quality ballast with appropriate properties to reduce ballast breakage, (7) providing enough confining pressure and using sufficient shoulder ballast and (8) providing efficient drainage systems and using proper subballast. More details can be found in Indraratna *et al.* (2011, 2007, 2006); Lieberenz and Weisemann (2002); Indraratna and Khabbaz (2008); Fatahi *et al.* (2008); Fatahi and Khabbaz (2011).

4.2.1 Geosynthetics

Geosynthetics can be used in railways for drainage, separation and reinforcement. Several works in the literature report reliable performance of geosynthetics in these applications and relevant aspects that must be considered (Selig and Waters, 1994; Raymond, 2002; Indraratna *et al.*, 2011, Fatahi *et al.*, 2011, for instance). A wide range of geosynthetics with different properties have been developed to meet highly specific requirements corresponding to various uses in new rail tracks and track rehabilitation for more than three decades. Enhancing the performance of rail tracks by composite geosynthetics is now extensively considered by rail industry. Based on relatively low cost and the proven performance of geosynthetics in a number of railway applications, many researchers (e.g. Raymond, 1994; Indraratna *et al.*, 2011; Lieberenz. and Weisemann, 2002; Indraratna and Khabbaz, 2008) have conducted experimental programs, field studies and numerical analysis to investigate the effects of the different types of geosynthetics on ballast degradation and fouling, track settlement and stabilisation of railway formation. Geotextiles are widely used as a strengthening and separation materials. Geotextile are usually placed on the subgrade and geogrids (or geocomposites) can be set between subballast and ballast layers. The fundamental and experimental studies (e.g. Indraratna *et al.* 2006)

proved that geogrids bonded with a drainage fabric (geotextiles) will increase the load bearing capacity of the ballast bed, while minimising the lateral movement of ballast and reducing degradation. Use of the composite geosynthetics also prevents the occurrence of liquefied soil (slurry) and its upwards pumping that would foul the ballast.

4.3 SLAB TRACKS

In all high speed rail systems, there is a choice between a slab track system and a ballasted track. Both have their own advantages and shortcomings. Ballast has been used since the beginning of railways in order to serve as the transition element between the sleepers and the formation, providing compliance and vibration damping, as well as surfacing and draining capabilities to the track. Ballasted degradation is the slow deterioration of the ballast particles due to traffic loading. Ballast breaks down and deteriorates progressively under heavy trainloads, settles differentially due to weak subgrade and poor drainage, fouls by fine particles due to clay pumping and ballast breakage and rail tracks buckles due to lack of confining pressure. The problems, associated with track foundation, result in costly rail track maintenance including restore the track alignment, ballast cleaning and ballast replacement (Indraratna *et al.*, 2011; Esveld, 2001). The increased maintenance costs and reduced life cycle of the track associated with higher transportation speeds, axle loads and traffic densities led to the appearance of the slab track in the 1960s.

Some of the advantages of the slab track with respect to the ballasted track are its higher geometric stability and reduced maintenance costs, as well as easier access to the track and evacuation due to the absence of blocking elements between rails. The general benefits of employing slab track can be summarised as follows: (1) reduction of the structure height (2) lower maintenance requirements and hence higher availability, (3) increased service life, (4) high lateral track resistance allowing higher speeds in combination with tilting technology, (5) great precision of track-geometry parameters by application of precise concrete sleepers, and (6) elimination of churning of ballast particles at higher speeds. However as explained by Esveld (2001), in comparison to the ballasted track the disadvantages of the slab track are generally: (a) higher construction costs, (b) large alterations in track position and superelevation can only be made possible by substantial amounts of work, (c) adaptability to larger displacements in the embankment is relatively small and (d) in case of derailment, repair works will take much more time and effort.

In order to reduce the high construction costs of high-speed rails, a new installation concept, called Rheda System, was developed by *Rail-One* company in Germany in 2000 (Esveld, 2003). Chief characteristics of the supporting concrete slab in this design include modified twin block sleepers with a lattice truss. By omitting the concrete trough, a complete step in the construction work sequence was eliminated. One of the main features of a slab track is the type of fastening which is applied to mitigate the transfer of noise from the train to the super structure.

There are a number of methods of fastening the rail to the slab and they have different vibration mitigation characteristics (Table 3). Within the different slab track types, floating slab tracks provide an effective way to reduce vibration transmission from railway traffic to the ground (Lombaert *et al.*, 2006). The floating slab track (FST) is a method of separating the slab track and the superstructure. This can be carried out using elastomers or springs. The amount of elastomer used can vary from fully supported to linear and point (discrete) supports. Separation can also be achieved by use of a large spring, which absorbs the noise and vibration. Some products allow their stiffness and height to be adjusted post construction. By adding an elastic layer beneath the slab, the natural frequency of the system is reduced, at the expense of increasing its cost.

Non-ballasted track concepts have already been applied to achieve high speed rail systems. Although slab track offers many benefits, its performance depends on careful design and construction methodologies. The main shortcoming of the slab track is its higher installation cost. Apart from that, railway administrations and design engineers often prefer to use traditional ballasted track designs instead of modern slab track designs, because extensive experience has been collected with the use of the former track type. Accordingly, it is suggested to use slab tracks in combination with ballasted tracks, with stabilised formation and inclusion of proper geosynthetics. However, slab tracks are strongly recommended for HSR bridges and tunnels to minimise the maintenance time and costs.

Table 3: Various types of slab track fastenings (data taken from Rhomberg Rail and Delkor Rail, 2012)

Fastening System	Approximate Noise Reduction Level	Description
Rail Pads	4 dB	Using a rubber pad placed between the rail and the base-plate or sleeper
Embedded Rail	5 dB	Wrapping the jacketed rails in an elastomer and a protective shell, inserted into slots in the slab track. The slot is then grouted to fill the gap between the slab and the rail.
Resilient Base Plates	10 dB	Having an elastomer, either pressed against the rail, between two metal plates, or underneath the baseplate.
Booted Sleepers	10 dB	Having the bottom and the sides of concrete sleepers covered in a rubber, which forms the 'boot' providing a separation between the sleeper and the slab
Isolated Slab Track (Ballast Mats)	20 dB	Ballast mats isolate the track structure from the supporting foundation or substrate, and can attenuate the transmission.
Floating Slab Track	25 dB	Using elastomers or springs. Separation can be achieved applying a large spring, which absorbs the noise and vibration.

Non-ballasted track concepts have already been applied to achieve high speed rail systems. Although slab track offers many benefits, its performance depends on careful design and construction methodologies. The main shortcoming of the slab track is its higher installation cost. Apart from that, railway administrations and design engineers often prefer to use traditional ballasted track designs instead of modern slab track designs, because extensive experience has been collected with the use of the former track type. Accordingly, it is suggested to use slab tracks in combination with ballasted tracks, with stabilised formation and inclusion of proper geosynthetics. However, slab tracks are strongly recommended for HSR bridges and tunnels to minimise the maintenance time and costs.

5 CONCLUSIONS

High speed rail systems have been one of the most innovative elements affecting passenger transport since the Second World War and Japan was effectively the birthplace of the high speed rail (HSR). It is clear that, high speed railways are expensive to construct, represent a considerable spending in the transport infrastructure, and produce economic and social effects. The factors that must be considered when implementing a high speed rail system can be complex and do not always work in favour of the nation building the rail line. Sometimes these factors such as the economic conditions of a nation or the natural geography cannot be directly controlled.

Some benefits of implementation of HSR can be summarised as follows: (1) reduction in carbon emissions, (2) increasing travel punctuality and safety for interstate commuters, (3) offering more comfort than airlines due to larger seats for the same ticket prices, more doors for exit and entrance, quieter cabins and no strict luggage weight restrictions, (4) contributing in development of regional areas and improving the land value along the demand corridors due to increased accessibility, (5) increasing desirability of Australia as a tourist destination, and as a host for world major events, (6) Reducing air pollution, vehicle accidents and traffic congestion, and (7) providing services to/from Sydney, while the Sydney Airport curfew is on after midnight.

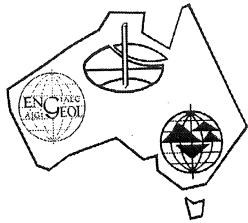
Two major issues connected to high speed train operations including critical velocity and transition problems have been discussed and various methods to avoid the train vibration at higher speeds are explained. It has been expressed that geosynthetics can provide an important option to improve track support stabilisation and thereby reduce the track maintenance costs and operation costs. In railroad construction, geosynthetics may be installed within or beneath the ballast or subballast layers.

The advantages of using slab tracks, also called ballast-less tracks, consist of rails fastened to continuous reinforced concrete slabs with free cracking, have been explained. In comparison to ballasted tracks, slab tracks reduce the construction height; reduce track maintenance like tamping; aligning and cleaning of tracks in stations; reduce the wear down of rail; provide better riding comfort at high speeds; provide higher availability, reduce vibration and secondary airborne noises; improve load distribution, thus reduce dynamic stresses on subsoil; provide high lateral and longitudinal track stability (reduce risk of track buckling) and eliminate problems with vegetation control, which is essential for a ballasted structure. On the other hand, the substantial higher cost of slab track construction makes the rail organisations to choose a combined system using slab tracks mostly for stations, tunnels, bridges and viaducts, while using stabilised ballasted tracks for the main corridor.

6 REFERENCES

- AECOM (2011), "High speed rail study phase 1" Prepared for Department of Infrastructure and Transport by AECOM Australia Pty Ltd with association with GRIMSHAW Architects, KPMG and SKM http://www.infrastructure.gov.au/rail/trains/high_speed/files/HSR_Phase1_Report.pdf. (Accessed on 8 July 2012).
- Arup-TMG (2001), "East coast very high speed train scoping study", (http://www.infrastructure.gov.au/rail/trains/high_speed (Accessed on 8 July 2012).
- Australian Government - Department of Infrastructure and Transport (2012), "High speed rail study: Moving forward with high speed rail." http://www.infrastructure.gov.au/rail/trains/high_speed/index.aspx (Accessed on 1 July 2012).
- Canberra Business Council (2008). "High speed rail for Australia: An opportunity for the 21st Century", (<http://www.canberrabusinesscouncil.com.au/submissions/files> (Accessed on 1 July 2012).
- Delkor Rail (2012), "Ballast-less track solutions", <http://www.delkorrail.com/railServices/pdfs>, (Accessed on 8 July 2012).
- Esvelde, C. (2003), "Recent developments in slab track", *European Railway Review*, 23 May 2003, pp. 81-85.
- Esvelde, C. (2001) "Modern railway track". MRT-Productions, Zaltbommel. ISBN 90-800324-3-3 (www.esveld.com).
- Fatahi, B. and Khabbaz, H. (2011). "Enhancement of ballasted rail track performance using geosynthetics", *Proceedings of the Geo-Hunan International Conference*, ed Adam F. Sevi; Jiuyuan Liu; Cheng-wei Chen; Sao-Jeng Chao, ASCE, USA, pp. 222-230.
- Fatahi, B. and Khabbaz, H. (2011). "Enhancement of ballasted rail track performance using geosynthetics", *Proceedings of the Geo-Hunan International Conference*, ed Adam F. Sevi; Jiuyuan Liu; Cheng-wei Chen; Sao-Jeng Chao, ASCE, USA, pp. 222-230.
- Fatahi, B., Khabbaz, H. and Ho, L.H. (2011), "Effects of geotextiles on drainage performance of ballasted rail tracks", *Australian Geomechanics Journal*, Vol. 46(4), pp. 91-102.
- Fatahi, B., Khabbaz, H. and Indraratna, B. (2008), "Analysis of matric suction effects induced by tree roots on rail track subgrade", *Conference on Railway Engineering*, Perth, WA, Australia, September 2008 in *Conference Proceedings: CORE2008 Conference on Railway Engineering*, ed. John Goodall, Bill Singleton, RTSA, Australia, pp. 599-610.
- Galvin, P., Romero, A. and Dominguez, J. (2010). "Fully three-dimensional analysis of high-speed train-track-soil-structure dynamic interaction". *Journal of Sound and Vibration* Vol. 329(24), pp.5147-5163.
- Givoni, M. (2006), "Development and impact of the modern high-speed rail", *Transport Reviews*.
- Gourvish, T. (2010), "The high speed rail revolution: history and prospects", *Report of High Speed 2*, London http://www.railwaysarchive.co.uk/documents/HS2_TheHighSpeedRailRevolutionHistoryAndProspects2010.pdf (Accessed on 7 July 2012).
- Indraratna B. and Khabbaz, H. (2008). "Geotechnical aspects of ballasted rail tracks and stabilising underlying soft soil formation". *Proceedings of the International Conference on Advances in Transportation Geotechnics*, Edited by Ellis, Thom, Yu, Dawson and McDowell, University of Nottingham, UK, 25-27 August, pp. 593-599.
- Indraratna, B., Khabbaz, H., Salim, W. and Christie, D. (2006), "Geotechnical properties of ballast and the role of geosynthetics", *Journal of Ground Improvement*, ISSMGE, Vol. 10 (3), pp. 91-101.
- Indraratna, B., Shahin, M.A. and Salim, W. (2007), "Stabilisation of granular media and formation soil using geosynthetics with special reference to railway engineering", *J. Ground Improvement*, Vol. 11(1), pp.27-43.
- Indraratna, B., Salim, W. and Rujikiatkarnjorn, C. (2011), "Advanced rail geotechnology - ballasted track", Taylor & Francis Group Publisher, United Kingdom.

- Lombaert, G., Degrande, G., Vanhauwere, B., Vandeborgh, B. and François, S. (2006), "The control of ground-borne vibrations from railway traffic by means of continuous floating slabs". *Journal of Sound Vibration*, Vol. 297, Issue 3-5, pp. 946-961.
- Lieberenz, K. and Weisemann, U. (2002), "Geosynthetics in dynamically stressed earth structures of railway lines", *Rail International, Schienen der Welt*. Vol. 33, pp. 30-39.
- Madhus, C., Lacasse, S., Kaynia, A. and Harvik, L. (2004), "Geodynamic challenges in high speed railways projects". *ASCE Proc. Geotechnical Engineering for Transportation Projects*, GSP 126.
- Okada, H. (2007), "High-speed railways in Asia: high-speed railways in China", *Japan Railway and Transport Review*, No. 48, pp. 22-29.
- Perry, J. (2010), "Strategic directions for Australian rail", *Rail Express Issue1*, June 2010, pp. 4-6.
- Raymond G.P. (1994), "Durability of geotextiles in railway rehabilitation", *Transportation Research Record*, Washington, DC USA, Issue 1439: pp. 12-19.
- Rhomberg Rail (2012), "Noise and vibration attenuation", <http://www.rhombergrail.com/en/home.html> (Accessed on 8 July 2012).
- Selig, E. T. and Waters, J.M., (1994), "Track geotechnology and substructure management", Thomas Telford Services, London, UK. Reprint 2007.
- William J. (2009), "Rail Race: Maglev or HSR, what is the future?", *The Rail Debate and Shape History*, Engineer News Record. <http://www.canv-maglev.com/pid5newsmedia/news/2009-07-21> ENR (Accessed on 8 July 2012).
- Woodward, P., Kacimi, A., Laghrouche, O. and Medero G. (2012), "Modelling the effects of ground and ballast stabilisation and reinforcement technologies on the dynamic performance of high speed ballasted railways", *Proc. ICGI 2012*, eds. Indraratna et al., 30 Oct.-2 Nov., University of Wollongong, Australia.
- Wright, M (2009), "Fly by rail – zero emissions transport capital to capital", *Beyond Zero Emissions Campaign*. <http://beyondzeroemissions.org/node/64> (Accessed on 4 July 2012).
- Yang Y.B., Hung, H.H. and Chang, D.W. (2003), "Train-induced wave propagation in layered soils using finite and infinite element simulation". *Soil Dynamics and Earthquake Engineering*, Vol. 23(4), pp. 263-278.



Australian Geomechanics Society

Sydney Chapter

AGS SYDNEY CHAPTER SYMPOSIUM, 10 OCTOBER 2012

Advances in Geotechnical Aspects of Roads and Railways

PAPER PEER REVIEW AND ASSESSMENT FORM

Paper Title: *General and Technical considerations for Implementing High Speed Rail systems in Australia*

Author(s): *Hadi Khabbazi and Behzad Fatahi*

Author Contact Details:

Peer Reviewer: *Hamid Reza Tabatabaie*

Peer Reviewer Contact Details: *city campus, PO Box 123 Broadway NSW 2007 / Ph: +61293149326*

Date of Review: *07/09/2012*

1. Subject Matter <input checked="" type="checkbox"/> Within scope of the Symposium <input type="checkbox"/> Not appropriate for the Symposium	2. Originality <input type="checkbox"/> Similar papers published by author(s) <input type="checkbox"/> Similar papers published by others <input checked="" type="checkbox"/> Unaware of similar papers
---	---

3. General Assessment	Please tick as appropriate and expand where necessary			
	Excellent	Good	Fair	Poor
Originality		<input checked="" type="checkbox"/>		
Technical quality		<input checked="" type="checkbox"/>		
Clarity of Presentation	<input checked="" type="checkbox"/>			
Importance in Field		<input checked="" type="checkbox"/>		

4. Title <input checked="" type="checkbox"/> Accurately reflects content <input type="checkbox"/> Needs revision (suggest alternative)	5. Language <input checked="" type="checkbox"/> Grammatically correct <input type="checkbox"/> Needs revision <input type="checkbox"/> Needs a careful editing
---	--

6. Abstract <input checked="" type="checkbox"/> Clear and adequate <input type="checkbox"/> Should be rewritten <input type="checkbox"/> Should be condensed <input type="checkbox"/> Missing	7. Presentation <input checked="" type="checkbox"/> Good <input type="checkbox"/> Contains irrelevant material <input type="checkbox"/> Should be rearranged
--	--

8. Illustrations <input checked="" type="checkbox"/> Good <input type="checkbox"/> Figures.....may be omitted <input type="checkbox"/> Extra figures required <input type="checkbox"/> Quality inadequate	9. Tables <input checked="" type="checkbox"/> Good <input type="checkbox"/> Should be rearranged <input type="checkbox"/> Tables.....may be omitted
--	---

AGS SYDNEY CHAPTER SYMPOSIUM, 10 OCTOBER 2012

Advances in Geotechnical Aspects of Roads and Railways

10. Abbreviations, formulae, units ✓ Confirm to acceptable standards Need revision Should be explained (formulae) A notation list is necessary	11. References ✓ Appropriate Incorrect Insufficient Too extensive
12. Grading of the Paper Excellent ✓ Very Good Good Fair Weak	13. Recommendation ✓ Publish Publish after minor amendments Major amendments required Do not publish

SELECTION OF PEER REVIEWER

A Peer Reviewer shall have at least 4 years relevant industry or academic experience, preferably be a Chartered Professional Engineer and member or eligible for membership with the Institution of Engineers Australia.

Peer Reviewers Qualifications

Tertiary Qualifications (Diploma/BE/BSc./Masters/PhD): Masters
Current Position: Research Assistant at UTS
Years of Experience & Area of Expertise: 12 years / Geotechnical Engineering
Member of IEAust or AGS: Yes ☒ No ☐ (AGS)
IEAust or AGS Membership Number if applicable:

Peer Reviewer's Comments

The paper is overall written very well.

Signed Author/s: Hadi Khabbazi

Date: 2/8/2012

Signed Peer Reviewer/s: [Signature]

Date: 6/8/2012

Notes: Please submit your final paper together with the completed paper peer review form to the organising committee for publishing in 2012 symposium proceedings.



**Australian
Geomechanics
Society**

ISSN 0818-9110

ADVANCES IN GEOTECHNICAL ASPECTS OF ROADS AND RAILWAYS

PROCEEDINGS OF THE 2012 AGS SYMPOSIUM

HELD IN

AUSTRALIAN NATIONAL MARITIME MUSEUM, DARLING HARBOUR, NSW

ON

October 10th 2012

Organising Committee: H. Khabbaz, C. Y. Tey, O. Stahlhut and C. Rujikiatkamjorn

**Published by
The Australian Geomechanics Society,
National Secretariat,
P.O. Box 955, ST IVES, NSW 2075**

**The AUSTRALIAN GEOMECHANICS SOCIETY is jointly sponsored by: Engineers, Australia and
The Australasian Institute of Mining and Metallurgy**



Responsibility for the content of this publication rests upon the authors and not on Engineers Australia, the NSW Maritime Panel nor the Australian Geomechanics Society. Data presented and conclusions developed by the authors are for information only and are not intended for use without independent substantiating investigation on the part of the potential user.

Australian Geomechanics Society

Geomechanics is the application of engineering principles to the earth sciences to improve continually the accuracy, efficiency, cost-effectiveness and safety of construction projects both above and below ground, including the recovery of the earth's mineral resources. It remains an imprecise discipline due to the infinite variety of conditions in the earth's crust but correspondingly offers a fascinating and rewarding field of research and practice.

The Australian Geomechanics Society was founded in 1970. Its origins lie in the National Committee of Soil Mechanics of the Institution of Engineers, Australia, established in 1953 and the call for a corresponding society in rock mechanics. In 1973 the society was expanded to include the third discipline of engineering geology and has remained substantially unchanged since that date.

The society is affiliated to the International society of Soil Mechanics and Foundation Engineering (ISSMFE), the International Society for Rock mechanics (ISRM) and the International Association for Engineering Geology and the Environment (IAEG).

The AGS is jointly sponsored by the Engineers Australia and the Australian Institute of Mining and Metallurgy

CORPORATE MEMBERSHIP OF THE AGS

\$770.00 and look at what your organisation gets -

Membership for two nominees who each receive:

- Membership fee (\$209)
- Membership of the three International Societies (\$176)
- IAEG Bulletin (\$44)

An extra copy of *Australian Geomechanics* for company library (\$154)

Acknowledgement in front section of every issue of *Australian Geomechanics*

Total benefit is \$836 All prices include GST.

Contact Peter Robinson on secretary@australiangeomechanics.org or go to www.australiangeomechanics.org for application forms and more information.

(c) Australian Geomechanics Society

All rights reserved. Other than brief extracts, no part of this publication may be produced in any form without the written consent of the publisher. The Society encourages reproduction of its publications and consent is usually looked upon favourably. It is a requirement that full and complete acknowledgement be cited when referencing articles published by AGS.

CONTENTS

Program	iii
Preface	iv
KEYNOTE PAPERS	
<u>FUTURE OF AUSTRALIAN RAIL TRACKS CAPTURING HIGHER SPEEDS WITH HEAVIER FREIGHT</u>	1
B. Indraratna, S. Nimbalkar and C. Rujikiatkamjorn	
<u>GEOTECHNICAL CHALLENGES FACING THE ROADS AND MARITIME SERVICES</u>	25
G. Vorobieff, S. Yuen and C. Walker	
TECHNICAL PAPERS	
<u>ADVANCED ANALYSIS OF TRACK FORMATION ON COODE ISLAND SILT</u>	33
D. Simmonds and S. Terzaghi	
<u>CASE STUDY OF RAILWAY EMBANKMENT STABILISATION WORKS AT MOOR PARK STATION WITH PROGRESSIVE SLOPE FAILURE</u>	41
C. Y. Tey	
<u>RAILWAY ENGINEERING AND GEOTECHNICAL ENGINEERING ARE THEY MARRIED YET?</u>	51
D. Christie	
<u>DEEP SOIL MIXING GROUND IMPROVEMENT TO MINIMISE DIFFERENTIAL SETTLEMENTS FOR RAIL EMBANKMENT CULVERT APPROACHES FOR THE HEXHAM NEW LOOP PROJECT, NSW</u>	59
S. Karasu, O. Batchelor and M. Griffiths	
<u>GENERAL AND TECHNICAL CONSIDERATIONS FOR IMPLEMENTING HIGH SPEED RAIL SYSTEMS IN AUSTRALIA</u>	67
H. Khabbaz and B. Fatahi	
<u>A NEW METHOD OF FILTRATION DESIGN ON RAIL TRACK SUBBALLAST</u>	79
L. D. O. Trani and B. Indraratna	
<u>PILES CREEK EMBANKMENT COLLAPSE – THE INVESTIGATIONS, THE EXPERT’S FINDINGS AND SUBSEQUENT IMPROVEMENTS IN ASSET MANAGEMENT OF CULVERT STRUCTURES ON MAJOR ROADS IN NSW</u>	89
C. Shackell and P. Retsos	
<u>COMPACTION AND COMPACTABILITY ASSESSMENT OF DIFFICULT SOILS - AN ALTERNATIVE APPROACH</u>	97
I. Driscoll, R. Kelly, S. Padina and M. Foweraker	
<u>GUIDELINES ON SETTLEMENT CRITERIA FOR DESIGN OF HIGHWAY PROJECTS</u>	103
P. K. Wong and S. Summerell	
<u>APPLICATION OF DYNAMIC COMPACTION IN RECLAIMED ROADS</u>	115
B. Hamidi, H. Nikraz and S. Varaksin	
<u>IMPACTS OF FRACTURING CAUSED BY VALLEY FORMATION AND PILLAR COLLAPSE ON THE HUNTER EXPRESSWAY PROJECT</u>	125
R.J. Symington, D.J. Och and O. Stahlhut	
<u>ACID SULFATE ROCK MANAGEMENT IN EARTHWORKS FOR ROADS</u>	133
C. Walker	
<u>FIELD BEHAVIOUR OF FILL STRUCTURES ON THE SOUTH WEST RAIL LINK</u>	147
A. Miller and C. Gani	
<u>GeoStrap® and EcoStrap™ REINFORCEMENTS FOR MSE STRUCTURES - A NEW APPROACH TO GEOSYNTHETIC SOIL REINFORCEMENT</u>	157
A. Ramirez and I. Rosler	

<u>COST EFFECTIVE DESIGN OF RAIL STRUCTURAL FILL ZONE AND ITS APPLICATION IN SOUTHERN SYDNEY FREIGHT LINE</u>	167
A. Butler and W. Deng	
<u>GEOTECHNICAL ASPECTS OF THE MID-WEST RAIL UPGRADE PROJECT IN WESTERN AUSTRALIA</u>	175
H. Acosta-Martinez, J. Fong, B. Decker and M. Gupta	
<u>INNOVATIVE TECHNIQUES IN THE CONSTRUCTION OF EMBANKMENT WIDENING</u>	189
J. Marwick, L. Wythes and D. Lidgard	
<u>COMPARISON OF DIFFERENT HARD ROCK DRILLING METHODS FOR BORED PILES</u>	197
Martin Larisch	
<u>SUCCESSFUL APPLICATION OF MIXED ABUTMENT CONSTRUCTION TO A FREIGHT RAIL FOUNDATION ON GRANULAR SOIL</u>	205
J. Marwick, M. Chung, M. Merry and P. Wanis	
<u>DETERMINATION OF MOISTURE CONTENT OF SUBGRADE SOIL USING ARTIFICIAL NEURO-ELECTRONIC CONTROL</u>	213
N. S. Shetu and M. A. Masum	
<u>FATIGUE AND STABILITY CHARACTERISTICS OF OPEN POROUS CEMENT BASE MATERIAL</u>	221
P. Hovagimian and M. Oeser	
<u>ANALYTICAL MODELLING OF PAVEMENTS UNDER MOVING LOADS</u>	229
S. Emami and M. Oeser	
<u>DIAPHRAGM WALL EMBEDMENT DEPTH DESIGN IN ROAD UNDERPASS TUNNEL PROJECT IN SINGAPORE</u>	239
W. Chen and T. Ho	
<u>DESIGN OF PILE FOUNDATION FOR AN INTEGRAL BRIDGE IN SOFT GROUND ON HUNTER EXPRESSWAY</u>	249
H. Zhang and J. Pan	
<u>GROUND INVESTIGATION IN THE SYDNEY CBD – A MORE SUSTAINABLE MODEL FOR THE FUTURE</u>	255
D.J.Och, S. Davies, D. Gilchrist, G. Kotze, A. Bowden and G. McNally	